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A team of eleven Ph.D. scientists and several graduate students was assembled at USU to work in close collaboration with scientists at the Air Force Geophysics Laboratory on a number of problems that are relevant to Air Force systems, including OTH radars, communications, and orbiting space structures. The overall goal of the research was to obtain a better understanding of the basic chemical and physical processes operating in the geoplasma environment, including the ionosphere, thermosphere, and magnetosphere. Some of the specific tasks included the following: (1) Studies of ionospheric structure and irregularities; (2) Study the feasibility of developing better operational ionospheric models for the Air Force; (3) Conduct model/data comparisons in order to validate the ionospheric models; (4) Study plasma convection characteristics in the high-latitude ionosphere; (5) Study magnetosphere-ionosphere coupling problems; (6) Construct a thermospheric general circulation model; (7) Develop a 3D, time-dependent model of the outer plasmasphere; (8) Develop a 3D, time-dependent MHD model of the earth's magnetosphere; (9) Conduct satellite drag studies; and (10) Study certain spacecraft-environment interaction problems, including those related to high-voltage power sources, spacecraft outgassing, and spacecraft charging at LEO altitudes.					
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Final Technical Report

USU Center of Excellence in Theory and  
Analysis of the Geo-Plasma Environment

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Contract: F49620-86-C-0109

## 1. INTRODUCTION

A team of eleven Ph.D. scientists and several graduate students was assembled at USU in order to establish a 'Center of Excellence in Theory and Analysis of the Geo-Plasma Environment'. The USU scientists worked in close collaboration with colleagues at the Air Force Geophysics Laboratories in Bedford, Massachusetts on a number of problems that were relevant to Air Force systems, including OTH radars, communications, and orbiting space structures. The overall goal of the research was to obtain a better understanding of the basic chemical and physical processes operating in the geoplasma environment, including the ionosphere, thermosphere and magnetosphere. Some of the more specific goals were as follows:

1. Investigate the effect of multi-cell convection patterns, plasma blob formation, and multiple arcs on the high-latitude ionosphere.
2. Study the production, transport, and decay of ionospheric irregularities and the associated plasma instabilities.
3. Investigate the coupling of high, middle, and low latitude regions of the ionosphere during the early stages of magnetic storms and substorms.
4. Study the effect of electrodynamic drifts, propagating density fronts, and shock formation on the dynamics of the inner magnetosphere.
5. Construct a numerical model of the earth's upper atmosphere (thermosphere) and couple it to a global ionospheric model.
6. The combined ionosphere-thermosphere model was to be used to investigate the effects of plasma convection, particle precipitation, and plasma blobs on the ionosphere-thermosphere system.
7. Couple global models of ionospheric conductivity, electric fields, and currents in order to study seasonal effects, hemispheric asymmetries, and the effects of discrete auroral arcs on ionospheric-magnetospheric dynamics.
8. Investigate ionosphere-magnetosphere coupling in the high-latitude region.



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## 2. USU-AFGL COLLABORATIVE EFFORTS

We have had ongoing collaborative projects with 11 scientists at the Air Force Geophysics Laboratories in Bedford, Massachusetts. The names of the AFGL scientists and their branches together with a brief description of the research is given below.

1. *D. Anderson* → We helped D. Anderson develop a *High Latitude Ionospheric Specification Model* for *Air Weather Services*, which was completed in the summer of 1989. This work required 54 ionospheric simulations to be run on the CRAY-2 computer at the Air Force Weapons Laboratory in New Mexico. We also developed an equatorial ionospheric model for D. Anderson that includes ion and electron temperatures.  
(LIS)
2. *J. Buchau* → We developed a procedure to model radio wave propagation through the disturbed storm ionosphere. The disturbance levels were defined from AFGL coordinated campaigns using ground-based, aircraft and satellite instrumentation. With J. Buchau we used these data to constrain the auroral dynamics and structure in our ionospheric model. Of particular interest were the auroral boundaries, i.e., the high-latitude edge (polar cap region) and the low-latitude edge (mid-latitude trough).  
(LIS)
3. *H. Carlson* → We conducted 3 ionospheric simulations for H. Carlson in order to determine the main mechanism responsible for the formation of the 'mid-latitude' density trough. The results are now being compared with measurements from the EISCAT incoherent scatter radar.  
(LIS)
4. *D. Cooke* → We studied a range of spacecraft-environment interactions that are relevant to D. Cooke's interests. These include outgassing from the Space Shuttle, plasma jets in the ionosphere from thrusters, solar cell charging processes and high-voltage spheres in the ionosphere. Several papers have been written on these topics and they are listed in the URI Publications section.  
(PHK)
5. *W. Denig* → An extensive four-day data set on the high-latitude ionosphere has been collected by W. Denig from incoherent scatter radars and DMSP satellites. This is the most comprehensive data set collected to date. In the near future, we will be doing ionospheric simulations for the conditions appropriate to this data set in order to study magnetic storm effects. These data are also being considered as a framework for coupling the magnetospheric and ionospheric specification modelling efforts.  
(PHG)

6. *D. Hardy* (PHP) → The use of D. Hardy's DMSP particle data is crucial to both ionospheric modelling and for future specification models. We incorporated the *Hardy et al.* [1985] auroral precipitation model as an input to our ionospheric model. With D. Hardy we looked at methods to represent the energy spectrum to improve the auroral ionization rates calculated by our ionospheric model. An energy flux threshold was established for the Hardy precipitation model.
  
7. *F. Marcos* (LIS) → We worked with F. Marcos to study satellite drag effects connected with changes in the neutral atmosphere. In particular, TIROS satellite data were used and predictions of satellite drag were contrasted using the standard *Kp* index versus the new Particle Precipitation Energy Index (PPE). A report has been written on this work and a paper is in preparation.
  
8. *N. Maynard* (PHG) → We conducted 36 ionospheric simulations for N. Maynard in order to contrast the ionospheric signatures of distorted 2-cell convection patterns against multi-cell patterns for northward IMF conditions. The simulations covered a range of seasonal and solar cycle conditions. A paper has been submitted for publication.
  
9. *F. Rich* (PHG) → We tested and implemented the Heppner-Maynard convection patterns digitized and coded by F. Rich. These patterns allow us to represent the convection IMF dependences in our ionospheric model. The AWS ionospheric specification model heavily depends on the densities our ionospheric model predicts for the different IMF convection patterns.
  
10. *E. Weber* (LIS) → We worked with E. Weber and his rocket data to see if we can deduce the electric field and particle precipitation features associated with sun-aligned arcs in the polar cap. These inputs are being used to run the ionospheric model with a local resolution on the scale of a few km to several 10's of km.
  
11. *J. Whalen* (LIS) → We conducted two ionospheric simulations for J. Whalen in order to study the longitudinal variation of the dayside electron density trough. The model results were then compared to his density data. Indeed, J. Whalen has brought to our attention the fact that a significant discrepancy exists during solar maximum conditions between observations and model predictions. (Since then this difference has been confirmed by D. Anderson using his ionospheric model.)

### 3. NATO/AGARD SYMPOSIUM

Up until the present time, studies of the aerospace propagation media tended to concentrate on localized phenomena or events. However, there is a range of phenomena which need for their elucidation observations and analysis on a global scale. Much of the localized ionospheric behavior is determined by coupling electrically to the distant ionosphere and solar wind, and by coupling dynamically and electrodynamically to higher and lower levels of the atmosphere. Therefore, global multistation/multiparameter observations are often necessary to provide the frame of reference for interpreting both stationary and propagating locally observed effects. Since communications, navigation, and surveillance systems operating in/through the aerospace EM propagation environment are affected by the state/variability of the propagation media, an understanding of the complex global interaction would improve the means of predictability and assessment of localized phenomena and suggest methods for mitigation of adverse propagation conditions.

With the above *theme* in mind, the NATO/AGARD Electromagnetic Wave Propagation Panel sponsored a symposium on "Ionospheric Structure and Variability on a Global Scale and Interaction with the Atmosphere and Magnetosphere". This symposium was held in Munich, Germany, from 16-20 May 1988. There were 47 invited and contributed presentations during the five-day meeting, and the papers presented were published in the conference proceedings. Dr. Schunk was a co-chairman of this NATO/AGARD symposium and was the editor of the proceedings. Dr. Schunk also presented a paper at the symposium.

#### 4. AWS PERSONNEL

Four Air Force personnel from Air Weather Services worked with us during the last 3 years on M.S. Theses. All have recently completed the requirements for a Masters Degree. Their names, thesis titles, and major professors are listed below.

1. A Time-Dependent Model for the Low Latitude Ionosphere

Capt. Gary Wells

Major Professor: R. W. Schunk

2. Status of Spacecraft Charging at Low Earth Orbit Altitudes: A Review

Capt. Mike Dwyer

Major Professor: R. W. Schunk

3. The Utility of Particle Precipitation Data as an Input to Thermospheric Density Models  
for Satellite Orbital Analysis

Capt. Kelly Hand

Major Professor: J. J. Sojka

4. Using the USU Ionospheric Model to Predict Radio Propagation Through a Simulated  
Ionosphere

Capt. Gary Huffines

Major Professor: J. J. Sojka

## 5. SCIENTIFIC ACCOMPLISHMENTS

In addition to the USU-AFGL collaborative efforts that were discussed in Section 2, we also conducted many additional studies as part of our University Research Initiative (URI) program. In total, 61 scientific papers have been published, 4 M.S. theses have been completed, and 89 presentations have been given at both national and international meetings during the 3 years that our URI program has been active. In addition, there have been several trips to AFGL in Boston, Massachusetts, and AWS in Colorado Springs, Colorado, in order to coordinate joint activities. Our URI Publications, URI Presentations, and a URI Travel Summary are included in this report.

Because we have published many papers, we cannot discuss all of the research that we conducted. Therefore, in the subsections that follow, we first outline the research we did in a given area and then highlight one of our studies in that area.

### 5.1. Ionosphere Structure & Irregularity Modelling

Density structures and irregularities are a common feature in the high-latitude ionosphere. There are small-scale ( $\lesssim 1$  km), medium-scale ( $\sim 10$  km), and large-scale ( $\gtrsim 100$  km) density structures. These structures have been observed in the *E*-region, *F*-region and topside ionosphere throughout the polar region, including the dayside cusp, polar cap, and auroral zone. The small-scale structures appear to be produced within and on the edges of the larger structures through plasma instabilities and are typically referred to as density irregularities. The medium and large-scale density structures have been called 'blobs', 'patches', and 'enhancements'. Relative to background densities, the perturbations associated with the medium and large-scale structures vary from about 10% to a factor of 100.

With regard to the medium and large-scale density structures, numerous structuring mechanisms have been proposed, including structured precipitation, structured electric fields, transport from distant sources, as well as time-varying convection and precipitation patterns. Because of the effect of density structures and irregularities on OTH radars and communications, we studied the origins, lifetimes, and transport characteristics of density structures with the aid of our three-dimensional, time-dependent ionospheric model. We studied the formation of plasma 'blobs' or 'patches' due to particle precipitation (Papers 4 & 59); the effect that structured electric fields have on the ionosphere (Paper 9); and the lifetimes and transport characteristics of density structures for different seasonal, solar cycle, and interplanetary magnetic field conditions (Papers 10 & 32). We also studied the extent to which large magnetic-field-aligned ion drifts affect ionospheric density structures (Paper 19).

In our study of the lifetime and transport characteristics of large-scale density structures, we considered both density depletions and enhancements. Specifically, a density structure was created at a particular location in the high-latitude *F*-region and its subsequent evolution was followed for different seasonal and solar cycle conditions as well as for different orientations of the IMF, i.e., different convection patterns. From this study we found that the lifetime of an *F*-region density structure depends on several factors, including the initial location where it was formed, the structure density, season, solar cycle, and convection pattern (IMF). For example, in summer the enhanced density of the structure can disappear in a few hours or last as long as 9 hours, while in winter a density structure can persist for as long as 24 hours. The structure will tend to last until the plasma convects into a region where the ion production rate is uniform and strong.

With regard to the transport characteristics of an *F*-region structure (blob or patch), this aspect was studied by creating a blob in the dusk sector of the polar cap and then following its evolution as it drifted in response to convection electric fields for different IMF orientations. In this case,



the adopted structure was assumed to have a very large density enhancement of a factor of 100 relative to background  $O^+$  densities and its 'initial' location was taken to be in the dusk-midnight sector at 2000 MLT. Six plasma flux tubes along the 2000 MLT meridian were selected to represent the initial width of the structure, with dipole latitude locations of 73.1, 74.3, 74.9, 75.5, 76.1, and 76.7°. These initial flux tube locations are shown in Figure 1 in a magnetic latitude-MLT reference frame. Also shown in Figure 1 is the subsequent spatial evolution of these plasma flux tubes for four different IMF configurations. The different cases were obtained from the *Sojka et al.* [1986] convection model with corotation added.

Not only can an initial density structure break up into smaller segments, but the subsequent evolution of the individual segments can be very different. This is shown in Figure 2, where  $N_m F_2$  is plotted versus time along five of the trajectories shown in Figure 1 for each of the four IMF cases and for winter and solar maximum conditions. The shading at the bottom of each plot indicates the times the convecting flux tubes are subjected to auroral precipitation. Dotted segments of the curves indicate the flux tubes are in darkness, while solid segments indicate sunlit conditions. Considering first the ( $B_z = -18\gamma$ ,  $B_y = 24\gamma$ ) case (left column), it is readily apparent that the temporal evolution of  $N_m F_2$  is very similar for the five trajectories because in this case the structure flux tubes stay together (see Figure 1). However, for the other southward IMF case ( $B_z = -18\gamma$ ,  $B_y = -24\gamma$ ), only two of the five structure flux tubes stay sufficiently close to each other to have similar temporal histories (top two plots). For the other three flux tubes, the  $N_m F_2$  variations are different because of different convection speeds along the trajectories, different exposures to auroral precipitation (see bottom of plots), and for one flux tube exposure to sunlight (solid curve segment). Note that the general conclusions reached above for southward IMF are also true for northward IMF (two columns on right). Finally, note that for a given IMF configuration and at a given time, the  $N_m F_2$  values can be different by more than an order of magnitude even though the five flux tubes started out under the same conditions.

## 5.2. Operational Ionospheric Models

Because the Air Weather Service is interested in improving its operational ionospheric models, we devoted a significant effort toward studying both numerical and empirical models of the ionosphere. We also tried to develop hybrid models, whereby empirical and numerical approaches are blended to obtain a reliable and efficient ionospheric model. This research has led to twelve publications (Papers 2, 3, 8, 11, 17, 20, 21, 23, 41, 42, 46, 47). We currently have the only numerical model of the ionosphere that is time-dependent and fully-global, and this model was used to study the seasonal behavior of the global ionosphere at solar maximum (Paper 20). We developed an efficient photochemical equilibrium model of ionospheric conductivity that includes the auroral oval (Paper 21), and we devised a simple procedure for improving the expression for  $T_e$  in the International Reference Ionosphere (IRI) (Paper 17). We also investigated alternative statistical models of auroral particle precipitation (Paper 2).

We compared the advantages and disadvantages of using numerical and empirical models of the global ionosphere (Papers 3 & 8), and we described the inputs that are needed in order to model ionospheric climatology and weather (Paper 23). In addition, we have written a chapter of a book that presents the complete mathematical description of our numerical ionospheric model (Paper 11). We also wrote a comprehensive review article on magnetosphere-ionosphere-thermosphere coupling processes for the *Solar Terrestrial Energy Program (STEP) Handbook* (Paper 61). The focus of the review article was on describing the major unresolved problems that need to be attacked in the coming decade.

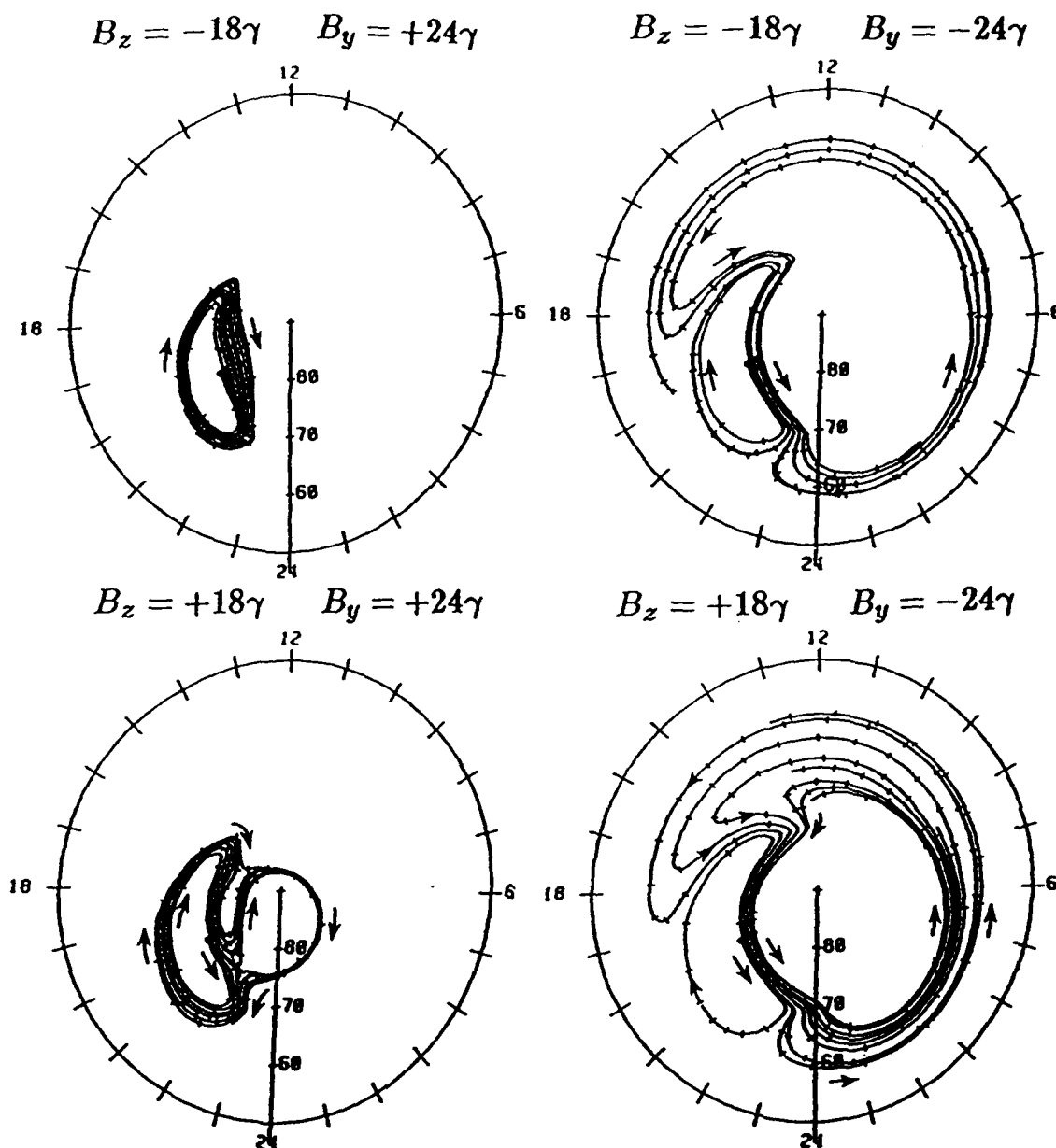


Figure 1. Plasma convection trajectories in a magnetic latitude-MLT reference frame for different IMF conditions. The trajectories were obtained from the *Sojka et al. [1986]* convection patterns with corotation added. The top dials show  $B_y$  positive and negative cases for southward IMF, while the bottom dials correspond to the same  $B_y$  cases for northward IMF. For each of the four IMF cases, six trajectories were followed for 24 hours starting at 2000 MLT and magnetic latitudes of 73.1, 74.3, 74.9, 75.5, 76.1, and 76.7°. The tick marks along the trajectories represent hourly intervals. From Paper 10.

## WINTER, SOLAR MAXIMUM

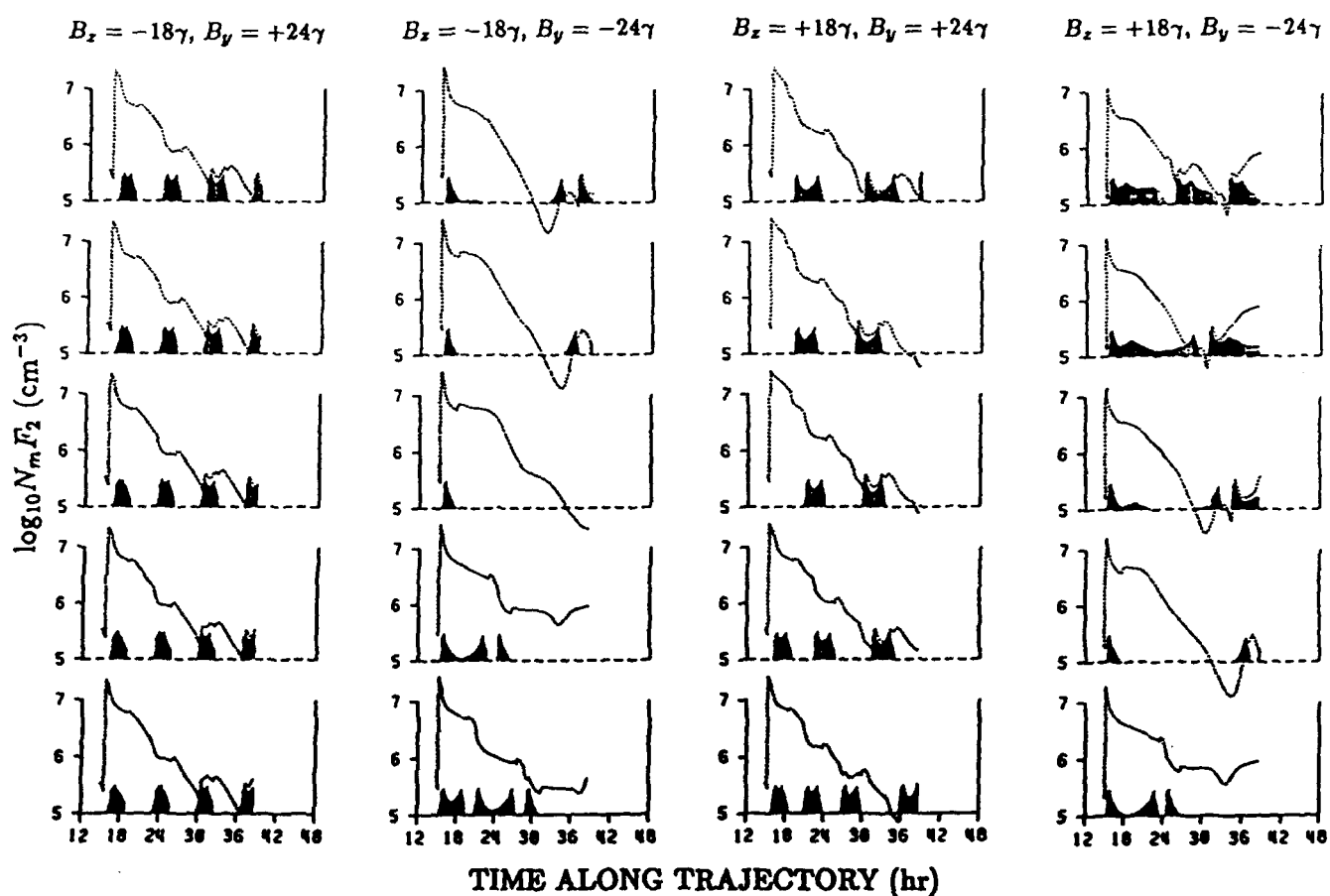


Figure 2.  $N_m F_2$  variation along five convection trajectories for four IMF cases in winter at solar maximum. The cases and trajectories are those shown in Figure 1. The shading at the bottom of each plot indicates the times the flux tubes are subjected to auroral precipitation. Dotted segments of the curves indicate the times the flux tubes are in darkness, while solid segments correspond to sunlit conditions. From Paper 10.

### 5.3. Model/Data Comparisons

In order to determine the validity of our global ionospheric model, we participated in several world-wide measurement campaigns. One of the programs is called SUNDIAL; 70 ground-based ionosondes and incoherent scatter radars make simultaneous measurements of ionospheric densities, temperatures, and flow velocities during 8-day campaigns. This effort has led to 8 publications (Papers 14-16, 30, 33, 36, 39, 57). We also participated in the MITHRAS campaign, which involved three high-latitude incoherent scatter radars (Paper 12) and in the GISMOS campaign (Papers 24 & 25). These model/data comparisons were extremely useful not only for verifying ionospheric model predictions, but for determining what model inputs are needed for operational conditions.

With regard to inputs for operational ionospheric models, our study using the MITHRAS incoherent scatter radar data has shown that one of the model inputs, the electron heat flux through the upper boundary, is important and yet is virtually unknown at the present time (Paper 12). In this study, we used Chatanika and Millstone Hill radar data taken simultaneously on June 27 and 28 in 1981. The electron density and temperature data were then compared with predictions made with our global ionospheric model. However, the model requires both the electron volume heating rate and the downward electron heat flux from the magnetosphere, which enters the calculation as an upper boundary condition at 1000 km. Unfortunately, there is a fairly large uncertainty associated with the calculation of the volume heating rate and the upper boundary heat flux is unknown. Consequently, these parameters could be varied, and we found that various combinations of the volume heating rate and the upper boundary heat flux provided equally good fits to the Chatanika and Millstone Hill radar data, as shown in Figure 3 for Millstone Hill and for one set of these parameters. Note that there is good agreement between the model and measured electron densities and temperatures at essentially all local times and at the three altitudes shown (195, 320 and 420 km).

For the calculations shown in Figure 3, the heat flux through the upper boundary was  $-0.7 \times 10^{10}$  eV cm<sup>-2</sup> s<sup>-1</sup>. However, as noted above, other values of the electron heat flux, ranging from 0 to  $2 \times 10^{10}$  eV cm<sup>-2</sup> s<sup>-1</sup>, could have been selected by varying the bulk heating rate. This indicates that the upper boundary heat flux is an important parameter for model predictions of *F*-region densities and temperatures. To further illustrate this fact, we calculated global distributions of ionospheric densities and temperatures both with and without a downward magnetospheric heat flux. The results are shown in Figure 4, where contours of  $T_e$  are plotted for 1700 UT and for downward electron heat fluxes of 0 (left panel) and  $1 \times 10^{10}$  (right panel) eV cm<sup>-2</sup> s<sup>-1</sup> at 1000 km. These temperatures were calculated for solar maximum, winter solstice, strong magnetic activity, and an asymmetric two-cell convection pattern with enhanced plasma flow in the dusk cell and a total cross polar cap potential of 90 kV. It is apparent from Figure 4 that a magnetospheric heat flux does not penetrate to altitudes as low as 180 km, since the  $T_e$  variation over the polar region is the same with and without the magnetospheric heat flux. At and above 300 km, on the other hand, the magnetospheric heat flux has a dominating effect on  $T_e$ . Not only are the electron temperatures significantly enhanced with the magnetospheric heat flux, but major  $T_e$  features are masked. In particular, the  $T_e$  hot spots in the dusk sector, which are related to enhancements associated with a sunlit trough and a  $T_i$  hot spot due to frictional heating, are masked by the elevated electron temperatures resulting from the magnetospheric heat flux. The elevated electron temperatures, in turn, significantly alter the *F*-region electron densities.

The above results clearly indicate that the downward electron heat flux from the magnetosphere can have a dramatic effect on the electron densities and temperatures, and hence, is an important parameter needed for operational models of the high-latitude ionosphere.

## MILLSTONE HILL

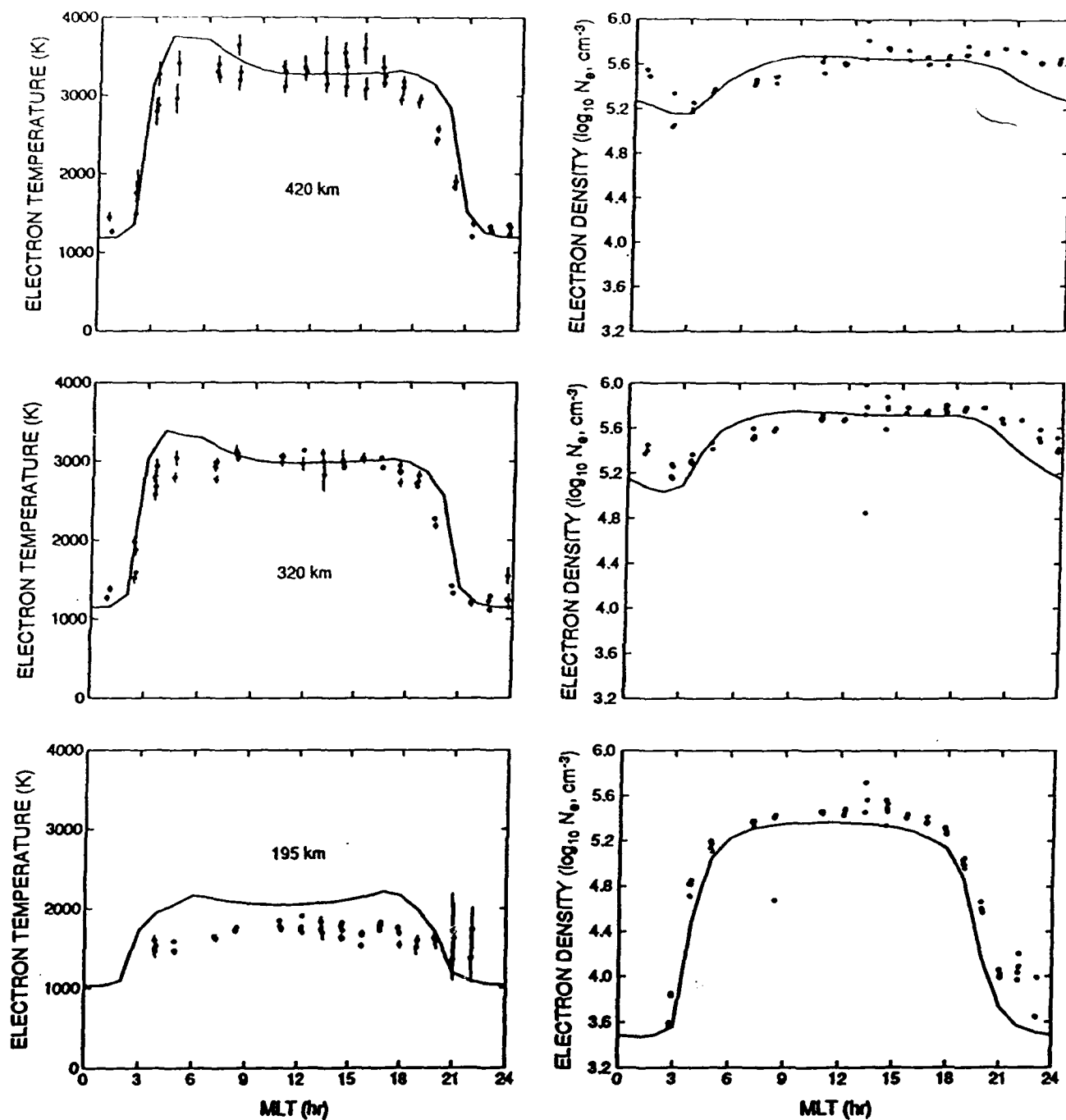


Figure 3. Comparison of the model electron density and temperature predictions with Millstone Hill measurements at 55° ( $\pm 1^\circ$ ) and at three different altitudes: 420 km (top panel); 320 km (middle panel); and 195 km (bottom panel). Electron temperatures are compared in the left column, and electron densities in the right. The model results are plotted as a solid line, and the radar measurements are plotted as solid circles. From Paper 12.

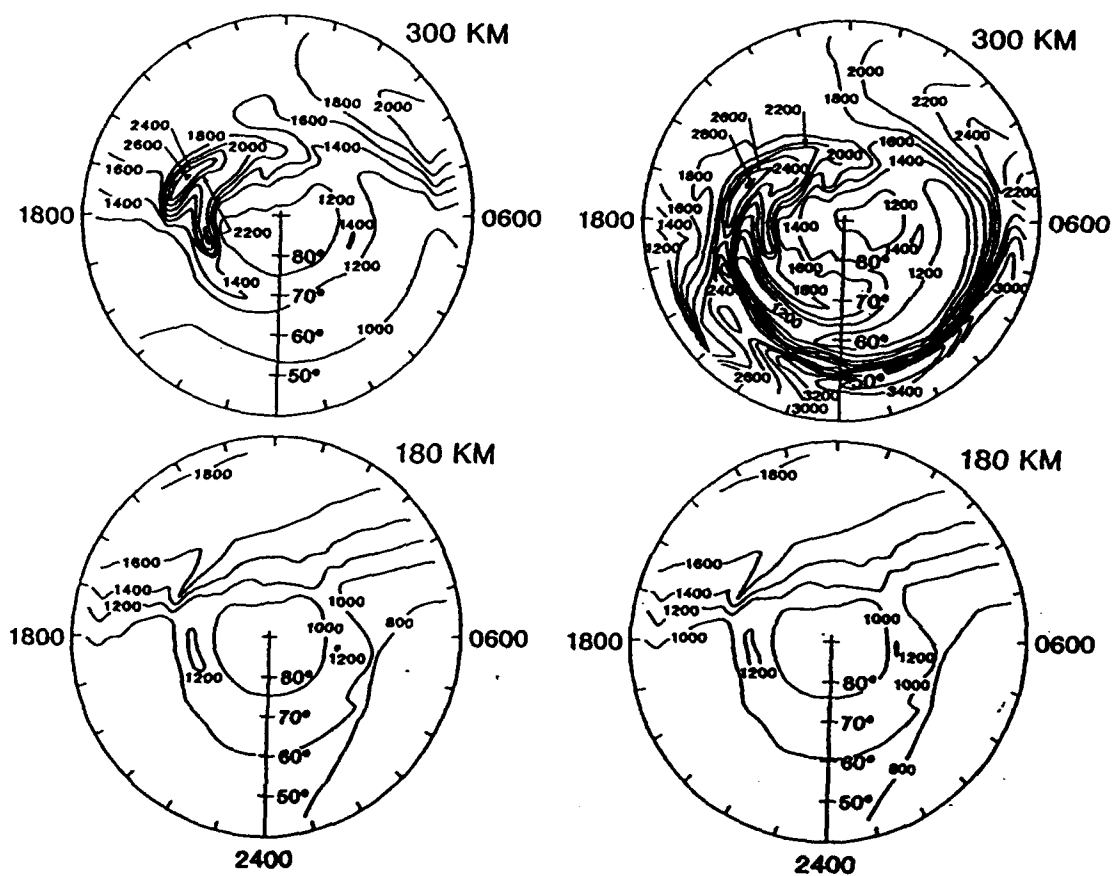


Figure 4. Contours of electron temperature at 1700 UT for upper boundary electron heat fluxes of 0 (left panel) and  $-1 \times 10^{13} \text{ eV cm}^{-2} \text{ s}^{-1}$  (right panel). An MLT-magnetic latitude coordinate system is used.

#### 5.4. Plasma Convection Studies

Convection electric fields have an important effect on the ionosphere at high latitudes. When the interplanetary magnetic field (IMF) is southward, the electric fields act to drive a two-cell pattern of ionospheric circulation, with antisunward flow over the polar cap and return flow equatorward of the auroral oval [Heppner, 1977; Heelis, 1984]. However, when the IMF is northward, multiple-cell or severely distorted two-cell convection patterns have been suggested [Burke *et al.*, 1979; Potemra *et al.*, 1984; Heppner and Maynard, 1987]. Using our three-dimensional, time-dependent ionospheric model, we studied the characteristic ionospheric signatures associated with two-, three-, and four-cell convection patterns. Our results indicate that there are major distinguishing ionospheric features associated with the different convection patterns and that these features should be easily observable from sites located in the polar cap (Paper 1).

For the case of a northward IMF, the measurements of electric fields are not sufficient to determine whether three-cell, four-cell, or severely distorted two-cell plasma convection patterns exist. Therefore, in an effort to shed light on this problem, we developed an ionospheric electric field model. With measurements of the field-aligned current and calculated ionospheric conductivities, we were able to calculate plasma convection patterns at *F*-region altitudes. Our calculations indicate that all of the proposed plasma convection patterns can exist, but in general, there appears to be a definite preference for the distorted two-cell configuration (Paper 13). This is shown in Figure 5, where we compare our calculated plasma convection patterns with those deduced by Friis-Christensen *et al.* [1985] and by Heppner and Maynard [1987]. As the IMF turns northward, our calculations indicate that the morning cell becomes somewhat elongated in roughly the sunward direction and the evening cell begins to wrap around the morning cell by extending into the morning sector. This process continues as the IMF becomes more strongly northward, until what was originally the evening cell becomes severely distorted, extending well into the early morning sector and almost completely surrounding the morning cell. What was originally the morning cell appears to shift into the polar cap. It is this cell, along with the distorted evening cell, which provides for sunward flow in the polar cap. As was seen in Figure 5, this transition in ionospheric convection with changing IMF is remarkably similar to the transition obtained from empirical studies of ground-based magnetometer measurements [Friis-Christensen *et al.*, 1985] and from empirical studies of satellite-based measurements of electric fields [Heppner and Maynard, 1987].

#### 5.5. Ionosphere-Magnetosphere Coupling

At high-latitudes the geomagnetic field lines are not dipolar, but instead stretch well beyond the orbit of the moon. Along these so-called 'open' field lines, ionospheric ions ( $H^+$ ,  $He^+$ ,  $O^+$ ) can escape into the magnetotail, which acts to drain the ionosphere and mass-load the magnetosphere [Dessler and Michel, 1966; Azford, 1968; Banks and Holzer, 1968]. The mass, momentum, and energy coupling associated with this plasma flow was studied in a series of papers (Papers 5, 6, 7, 22, 31, 37, 40, 43).

One of our goals was to study the stability of the plasma outflow (polar wind). In particular, as the plasma expands in the diverging geomagnetic field, the  $H^+$  velocity distribution becomes non-Maxwellian. The non-Maxwellian features include a temperature anisotropy, with the parallel  $H^+$  temperature greater than the perpendicular temperature, and an asymmetry, with an elongated tail in the upward direction. These distortions from a Maxwellian increase with altitude, and at 10  $R_e$  the parallel-to-perpendicular temperature ratio is about 50 and the tail on the distribution is sufficiently long to move the drift velocity point off the peak of the distribution. Such highly non-Maxwellian features are potentially unstable, and if the polar wind was unstable this could significantly affect ionosphere-magnetosphere coupling. Consequently, Barakat and Schunk [1987] studied the stability of the polar wind with regard to the excitation of electrostatic waves. Despite

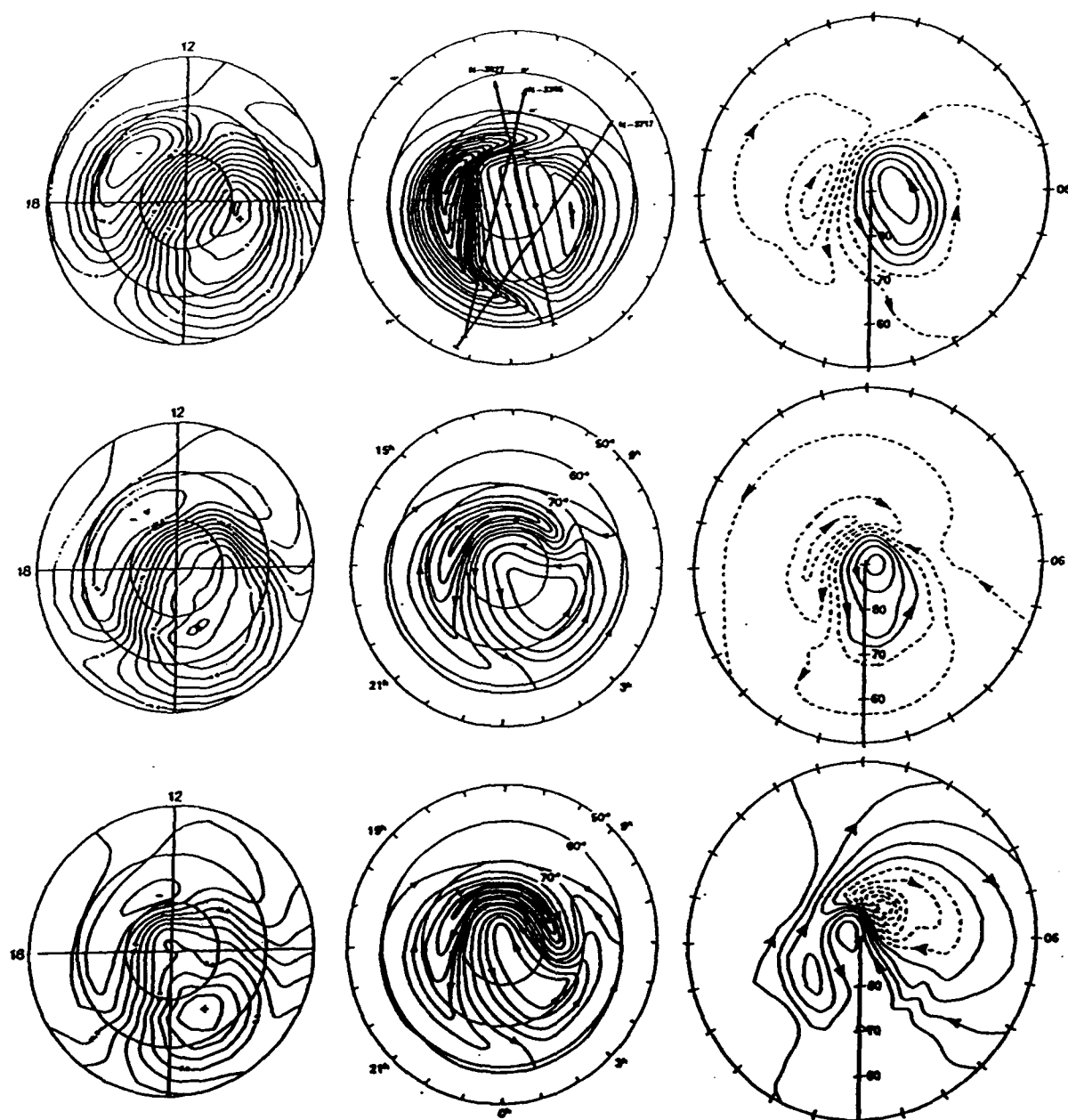


Figure 5. Summary of three different empirical studies of the dependence of ionospheric convection on the  $z$  component of the IMF. The left column is from *Friis-Christensen et al. [1985]*, the middle column is from *Heppner and Maynard [1987]*, and the right column is our results. The top row is for southward  $B_z$ , the middle row is for weakly northward  $B_z$  ( $B_z = 0$  for the *Friis-Christensen et al. [1985]* results), and the bottom row is for  $B_z$  more strongly northward. From Paper 13.



the highly non-Maxwellian character of the  $H^+$  velocity distribution, the polar wind was found to be stable for a wide range of conditions.

Although the classical polar wind occurs the bulk of the time, during increasing magnetic activity and for certain flux tubes that pass through the cusp, the classical picture of the polar wind may not be appropriate. Figure 6 shows schematically a possible mechanism by which the polar wind deviates from its classical picture due to plasma convection. Consider a magnetic flux tube in the subauroral region immediately before it convects into the cusp region. This flux tube is originally filled with a plasma of the classical polar wind type. As the flux tube convects into the cusp region, the ions at low altitudes undergo parallel and perpendicular energization. These energetic ions eventually catch up with the slower "classical" polar wind at high altitudes as the flux tube convects into the polar cap region. This process results in energetic ion beams and/or conics passing through the classical polar wind.

The stability of a cusp-generated  $H^+$  beam passing through the classical polar wind was studied in Paper 31. The stability of the plasma was studied for a range of electron-ion temperature ratios ( $0.1 \leq T_e/T_i \leq 10$ ) and beam-to-background ion density ratios [ $0.1 \leq n_b/(n_b + n_i) \leq 0.9$ ]. Table 1 summarizes the results found in our study. For most of the cases, the polar wind is unstable for fairly small ion beam-plasma relative drifts. The plasma is more unstable for larger electron temperatures and for comparable ion beam and background ion densities ( $n_b \sim n_i$ ). For large electron temperatures ( $T_e = 10T_i$ ), the ion/ion plasma-acoustic instability is the first mode to be triggered, and the waves that propagate parallel to the magnetic field are destabilized first. For lower electron temperatures, on the other hand, the ion/ion cyclotron modes, which propagate obliquely, tend to be triggered first.

### 5.6. Thermospheric General Circulation Model

In collaboration with Herb Carlson at AFGL, we initiated the development of a time-dependent, three-dimensional model of the earth's upper atmosphere (thermosphere). The model is based on a numerical solution of the coupled continuity, momentum, and energy equations for the neutral gas including interactions with ionospheric electrons and ions. The model is a high-resolution, multi-species model and it was designed so that the global grid system is arbitrary. This is superior to the NCAR thermospheric general circulation model, which is restricted to a fixed grid system. With our thermospheric circulation model, we are able to place many grid points in the regions where relatively narrow ionospheric features occur, such as in the auroral oval and main trough. Currently, a preliminary version of the model is running, but the heating and cooling rates need to be improved and then the model needs to be coupled to our global ionospheric model before it can be used for practical applications.

### 5.7. Outer Plasmasphere Studies

One of the important unresolved problems in ionosphere-plasmasphere coupling concerns the refilling of depleted flux tubes after geomagnetic storms. Specifically, it is not clear whether the plasmasphere fills from the top (equatorial region) to the bottom (ionosphere) or vice versa. Banks *et al.* [1971] postulated that the refilling of the plasmasphere following magnetic storms occurs via upward supersonic plasma flows from the conjugate ionospheres. It was further suggested that the interaction of the supersonic counterstreaming flows in the equatorial region leads to the formation of a pair of electrostatic shocks. Behind the shocks is a relatively high-density, high-temperature plasma. The initial refilling of the flux tube occurs as the shocks move down the flux tube toward the conjugate ionospheres at a fairly low speed. Subsequent hydrodynamic modelling of this process appears to have confirmed this postulation [Khazanov *et al.*, 1984; Singh *et al.*, 1986]. However, both analytical studies and small-scale numerical simulations indicate that the initial formation of

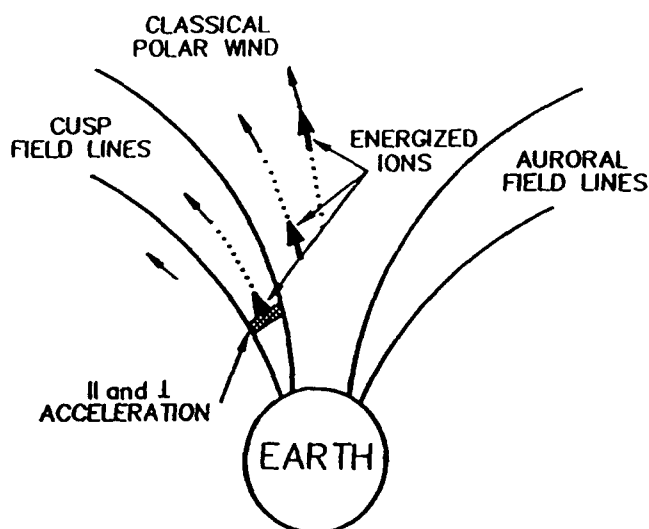


Figure 6. Schematic diagram showing how ion acceleration in the cusp coupled with horizontal plasma convection can lead to an energetic ion population passing through the classical polar wind. From Paper 31.

Table 1.  $H^+$  beam-plasma normalized critical drift velocity above which the plasma is unstable for different electron-to-ion temperature ratios and different beam-to-background ion density ratios. The beam temperature is ten times smaller than the background ion temperature ( $T_b/T_i = 0.1$ ). The critical drift velocity is normalized with respect to the parallel thermal speed of the background ions. From Paper 31.

$T_e/T_i$	$n_b/(n_b + n_i)$		
	0.1	0.5	0.9
0.1	> 11	3.4	> 11
1.0	2.7	0.71	1.30
10	0.3	0.18	0.26

the shocks is unlikely and that a simple counterstreaming of the flows should occur [Schulz and Koons, 1972; Singh and Schunk, 1983]. This latter conclusion appears to have been substantiated by observations of counterstreaming plasma flow during flux tube refilling [Sojka *et al.*, 1983; Decreau *et al.*, 1986].

In order to study this problem, we developed a *multi-stream*  $H^+$  model of plasmasphere refilling (Papers 34 & 55). The model is based on a numerical solution of the macroscopic, time-dependent, nonlinear, hydrodynamic equations for  $H^+$  and electrons. The equations are solved along a dipolar magnetic field line from about 500 km in one hemisphere to the same altitude in the conjugate hemisphere, as shown in Figure 7. The unique feature of the model is that it allows for separate  $H^+$  streams from the conjugate hemispheres, while the hydrodynamic models discussed above are based on a single-fluid  $H^+$  formulation [Khazanov *et al.*, 1984; Singh *et al.*, 1986]. A comparison of the predictions of the single-fluid and multi-stream models is shown in Figure 8 for a specific refilling scenario. In this scenario, at  $t = 0$  a plasma flux tube is depleted to simulate the process that occurs during a magnetic storm. The subsequent refilling is shown in the top panel of Figure 8 for the single-fluid model and in the bottom panel for the multi-stream model. With the single-fluid model, when the upflowing streams from the conjugate ionospheres meet at the equatorial plane, a pair of shocks form and then slowly propagate down to the conjugate ionospheres. Between these shocks is a high density plasma. However, this prediction is an artifact of the single-fluid model because in this case only one fluid velocity exists at any point along the flux tube. Therefore, when the two supersonic  $H^+$  streams from the opposite hemispheres meet at the equator, the sum of equal and opposite drift velocities is zero and a shock-pair is automatically triggered. This shock-pair is not triggered when a more rigorous two-stream hydrodynamic model is used. In this case, the two streams from the opposite hemispheres are modelled as separate fluids, but are allowed to interact via collisions and the polarization electrostatic field. Now, when the two streams meet at the equatorial plane, they simply interpenetrate and no shocks form (Figure 8, bottom panel). Therefore, in a given situation, the results one gets is directly related to the model adopted and care must be exercised in selecting models.

### 5.8. MHD Magnetosphere Model

In support of the work done in the Magnetospheric Physics Branch at AFGL, which is headed by N. Maynard, we initiated the development of a time-dependent, three-dimensional, magneto-hydrodynamic model of the earth's magnetosphere. The model is numerical and the appropriate MHD continuity, momentum, and energy equations are solved along with Maxwell's equations for the self-consistent electric and magnetic fields. In the model, a supersonic solar wind plasma flows past the ionized, magnetized environment that surrounds the earth, and as time evolves the magnetosphere forms. At the present time, the full three-dimensional model has been coded, but we are only running the symmetric 2-D version during the current testing phase.

### 5.9. Spacecraft-Environment Interaction Studies

Scientists at AFGL, particularly Dr. Cooke, encouraged us to study certain spacecraft-environment interaction problems that are relevant to Air Force interests. We were encouraged to study spacecraft charging, outgassing from orbiting systems, and problems related to high-voltage power sources exposed to the space environment. Currently, we are working on problems in all three areas. Mike Dwyer of AWS has conducted a comprehensive literature search on the current state of knowledge of spacecraft charging in low earth orbit (LEO); this effort produced an M.S. degree for Mike. We also initiated a model development that will allow us to study the effect on the ionosphere of high-voltage (50,000 Volts) power sources (Papers 35 & 38). In addition, we studied

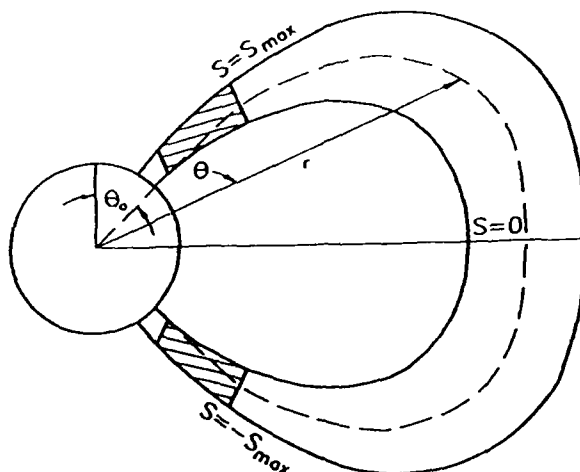


Figure 7. Geometry of the closed geomagnetic flux tube used to model plasmasphere refilling. The symbols  $\theta$  and  $r$  are colatitude and geocentric distance, respectively. The ionosphere is indicated by the cross-hatched portion and  $s = \pm s_{\max}$  correspond to the boundaries in the conjugate ionospheres. From Paper 34.

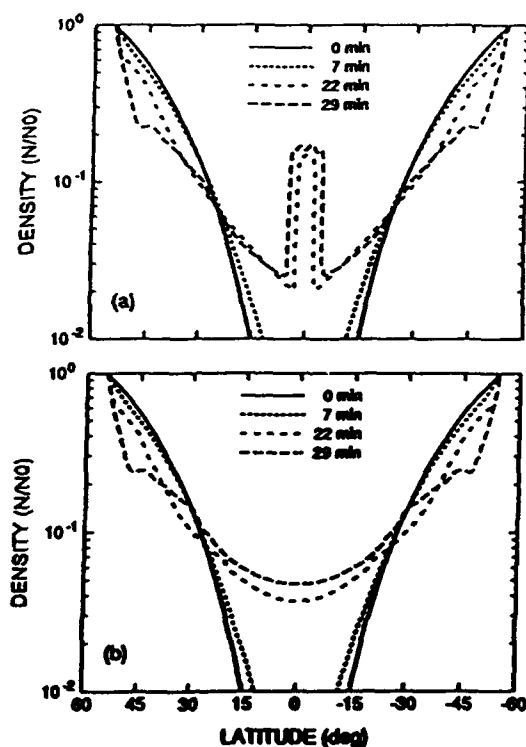


Figure 8. Electron density as a function of dipole latitude for the single-stream model (top panel) and for the two-stream model (bottom panel). The different curves show the evolution with time as the flux tube fills. The times are from the start of the model run. From Paper 34.

the sheath formation and current leakage associated with the operation of a solar array in the low-earth-orbit (LEO) plasma environment (Paper 56).

We also devoted a major effort studying the interaction of a large outgassing, orbiting vehicle with the ambient atmosphere and ionosphere at LEO altitudes. We studied the overall plasma and neutral gas perturbations in the vicinity of the vehicle (Papers 48, 50, 51), the changing characteristics of the vehicle (Papers 52, 53, 54), the wave noise in the vicinity of the vehicle (Paper 49), and the electromagnetic waves that propagate away from the vehicle (Paper 60).

One of our studies was concerned with the interaction of a high-voltage sphere with the plasma environment at LEO altitudes. This study was motivated by the fact that in the coming decade large space structures with high-power sources will be orbiting the Earth at ionospheric altitudes. Exposed voltages on any part of the structure will cause a current flow between the exposed element and the ambient plasma, which in turn may cause a power loss or arcing. In an effort to better understand high-voltage current collection at LEO altitudes, we developed a model for the interaction of a positive high-voltage sphere with a magnetized plasma. The model is based on a numerical solution of the time-dependent, three-dimensional, nonlinear fluid equations for  $O^+$  and electrons and the Poisson equation. Simulations were conducted for both low (10 V) and high (10,000 V) voltage spheres in both low ( $10^4 \text{ cm}^{-3}$ ) and high ( $10^6 \text{ cm}^{-3}$ ) density background ionospheres. The magnetic field strength was also varied in order to determine its effect on the current collection. A summary of the simulation results is shown in Figure 9, where snapshots of the electron density distributions about the sphere are shown at a selected time for four different cases. In all simulations, an electron density torus forms around the sphere in the equatorial plane at early times. The torus rotates about the sphere in the  $\mathbf{E} \times \mathbf{B}$  direction. The characteristic time for both the torus formation and the rotation is determined by the potential on the sphere and the electron cyclotron frequency. The torus size and density are larger for higher sphere voltages and lower ionospheric densities. At later times, the outer edge of the torus becomes elongated along the magnetic field, and the bulk of the region perturbed by the sphere is contained within a cylindrical volume. These new and interesting results have recently been confirmed by laboratory experiments.

In another study, we modelled the charging characteristics of a solar array that was exposed to an ionospheric plasma. In particular, we modelled the temporal evolution of the plasma surrounding a series of solar cells that were connected with metal interconnectors. The simulations were conducted with a 2.5-dimensional particle-in-cell numerical technique. With this technique, individual particles are followed as they move in response to self-consistent electric fields, which are obtained at each time step via a solution of Poisson's equation. This method has an advantage over other methods in that the complete dynamics is modelled including the possibility of wave excitation and wave-particle interactions.

In our first series of simulations, a 'positive' voltage was suddenly applied to a solar array and the subsequent response of the plasma was modelled (Paper 56). We considered voltages of 100 and 250 volts and background ionospheric densities of  $10^4$  and  $10^6 \text{ cm}^{-3}$ . For these cases, we modelled the charging characteristics both with and without secondary electron emission from the solar cell cover glass. Examples of the simulation results are shown in Figures 10a and 10b for cases without and with secondary electron emission, respectively. These cases are for a 250 volt solar cell pair (half of each is shown) attached with a 1 mm interconnector. The solar cells are at the bottom of the simulation domain with the interconnector in the middle. The simulation domain is filled with a 0.1 eV  $O^+$ -electron plasma at a density of  $10^6 \text{ cm}^{-3}$  at the start of the simulation and then the 250 volts are applied to the solar cells ( $t = 0$ ). The results shown in Figures 10a and 10b are contours of electrostatic potential at  $t = 200\omega_{pe}^{-1}$ . Note that without secondary electron emission (Figure 10a), electron shielding occurs and a distinct sheath forms around the interconnector. It is

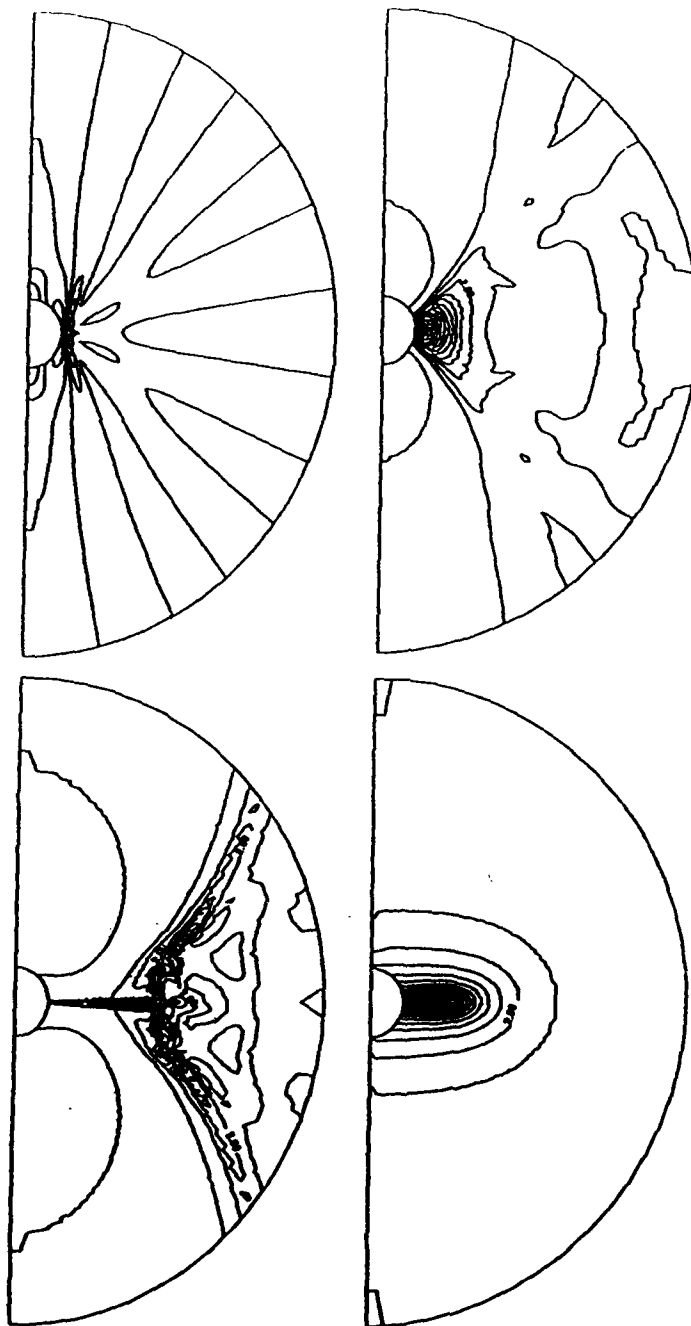


Figure 9. Contours of  $\hat{N}_e$  at  $\hat{t} = 20$  for the four cases. The upper-left panel is for case 1 ( $\Phi_0 = 10$  V,  $n_0 = 10^6 \text{ cm}^{-3}$ ,  $\hat{\Omega}_e = 1$ ); the upper-right panel is for case 2 ( $\Phi_0 = 10$  V,  $n_0 = 10^4 \text{ cm}^{-3}$ ,  $\hat{\Omega}_e = 1$ ); the lower-left panel is for case 3 ( $\Phi_0 = 10,000$  V,  $n_0 = 10^6 \text{ cm}^{-3}$ ,  $\hat{\Omega}_e = 1$ ); and the lower-right panel is for case 4 ( $\Phi_0 = 10,000$  V,  $n_0 = 10^6 \text{ cm}^{-3}$ ,  $\hat{\Omega}_e = 0.1$ ). The plots are linear in  $r$  from the sphere radius of 10 to 94 cm. The contour spacing for  $\hat{N}_e$  is 0.5. The "actual" time for case 2 is ten times longer than for the other cases because of the lower plasma frequency  $\omega_{pe}$ . The magnetic field is in the vertical direction. From Paper 35.

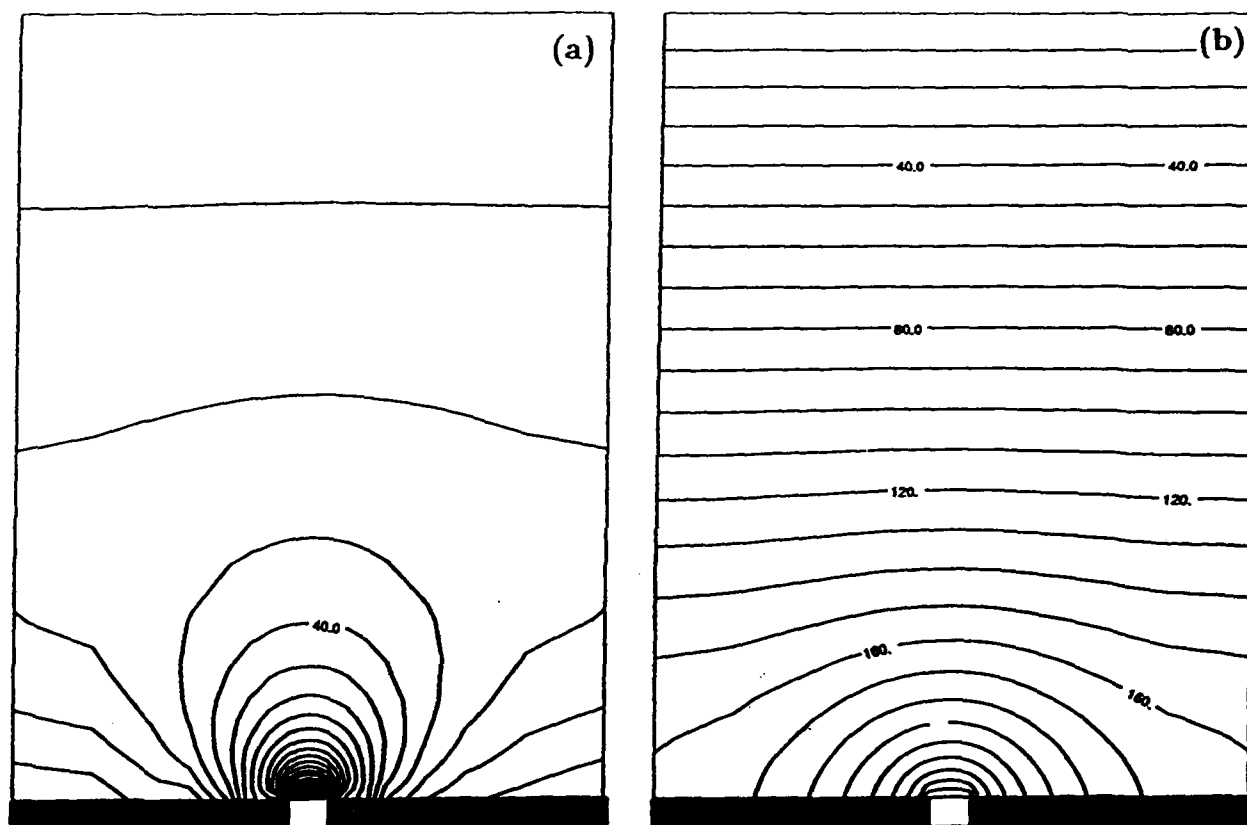


Figure 10. Potential distribution in the vicinity of two 250-volt solar cells connected with a 1 mm interconnector. The solar cells are at the bottom boundary of the simulation domain with the interconnector in the middle. The potentials are shown at  $t = 200\omega_{pe}^{-1}$ . Panel (a) is without and panel (b) is with secondary electron emission. From Paper 56.

in this region where the electric fields are strong. With secondary electron emission (Figure 10b), on the other hand, a planar potential structure forms that extends across the solar cell surfaces. Hence, secondary electron emission acts to extend the region containing high electric fields.

As a final example of what we have accomplished, we briefly discuss our spacecraft outgassing model. We developed a model which describes the interaction of a large, outgassing, orbiting vehicle with the ambient atmosphere at LEO altitudes. The model uses a finite difference method to solve the Boltzmann equation including the effect of collisions between gaseous particles. Distribution functions are obtained for each of several interacting gas species, and the results are presented in terms of macroscopic gas parameters. Figure 11 shows the number densities and temperatures of O, N<sub>2</sub>, and H<sub>2</sub>O in the vicinity of an outgassing Space Shuttle at LEO altitudes. For this example, the water outgassing rate assumed is approximately that of the Space Shuttle flash evaporator.

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# SL-2 Conditions

## Integrated moments over entire grid

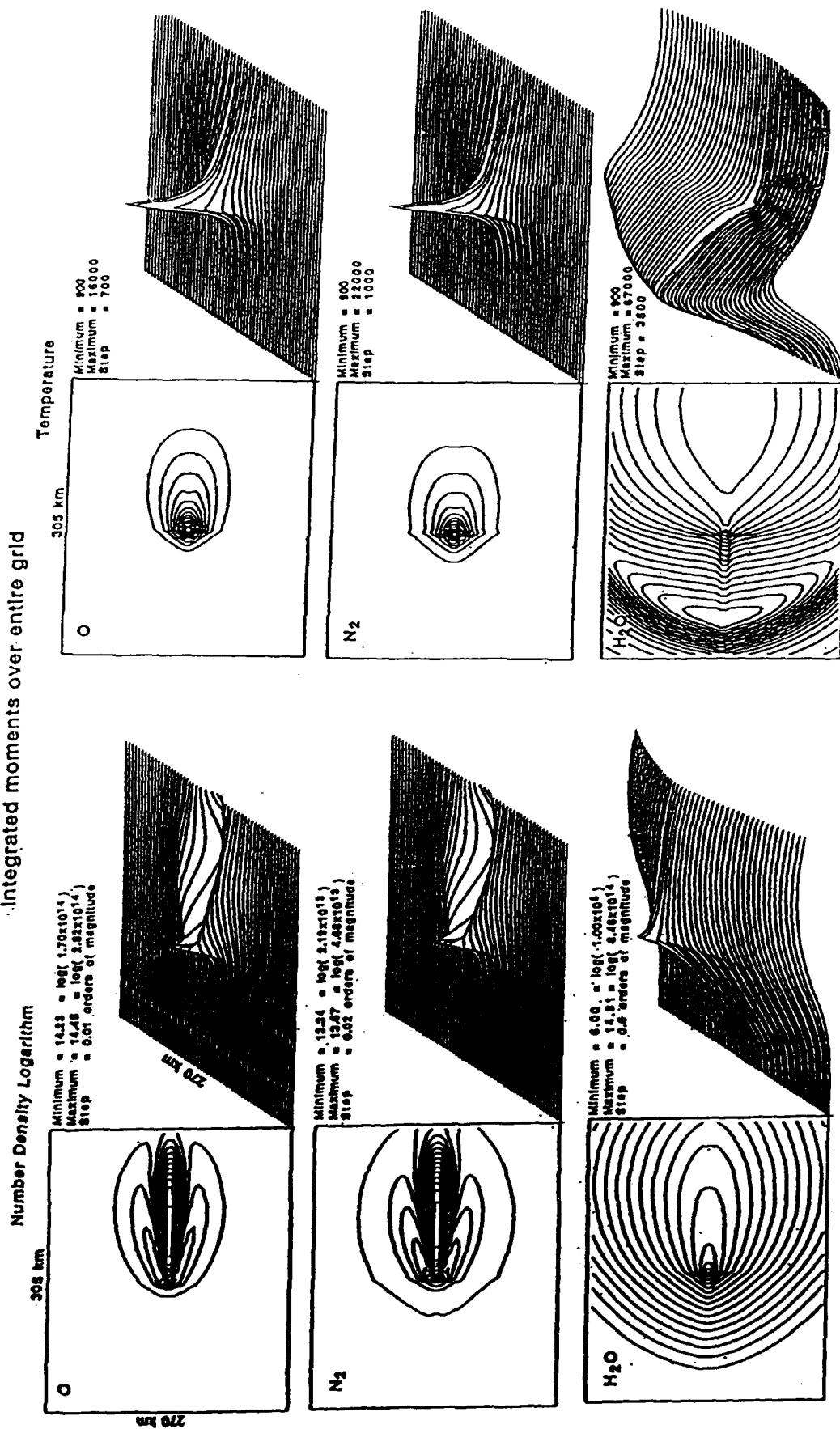


Figure 11. Number density (left panel) and temperature (right panel) of O, N<sub>2</sub>, and H<sub>2</sub>O in the vicinity of an outgassing Space Shuttle at LEO altitudes.

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52. W. J. Raitt, Space poser experiments aboard rockets, SPEAR-1, Final Report, October, 1988.
53. B. E. Gilchrist, P. M. Banks, T. Neubert, P. R. Williamson, N. B. Myers, W. J. Raitt, and S. Sasaki, Electron collection enhancement arising from neutral gas jets on an isolated charged vehicle in the ionosphere, *J. Geophys. Res.*, in press.
54. N. B. Myers, W. J. Raitt, B. E. Gilchrist, P. M. Banks, T. Neubert, P. R. Williamson, and S. Sasaki, A comparison of current-voltage relationships of collectors in the Earth's ionosphere with and without electron beam emission, *Geophys. Res. Lett.*, *16*, 365-368, 1989.
55. C. E. Rasmussen and R. W. Schunk, A three-dimensional time-dependent model of the plasmasphere, *J. Geophys. Res.*, in press.
56. H. Thiemann and R. W. Schunk, Sheath formation around biased interconnectors and current collection in a LEO-plasma as seen by PIC simulations, *J. Spacecraft and Rockets*, in press.
57. R. Sica, R. W. Schunk, and P. J. Wilkinson, A study of the undisturbed mid-latitude ionosphere using simultaneous multiple site ionosonde measurements, *J. Geophys. Res.*, in press.
58. N. C. Maynard, J. J. Sojka, R. W. Schunk, J. P. Heppner, and L. H. Brace, A test of convection models for IMF *B<sub>x</sub>* north, *Planet. Space Sci.*, submitted.
59. J. Labelle, R. J. Sica, C. Kletzing, G. D. Earle, M. C. Kelley, D. Lummerzheim, R. B. Torbert, K. D. Baker, and G. Berg, Ionization from soft electron precipitation in the auroral *F*-region, *J. Geophys. Res.*, submitted.

60. C. E. Rasmussen, P. M. Banks, and K. J. Harker, The excitation of plasma waves by a current source moving in a magnetized plasma: Two-dimensional propagation, *J. Geophys. Res.*, submitted.
61. R. W. Schunk, Magnetosphere-ionosphere-thermosphere coupling processes, *STEP Handbook*, 52-110, 1988.

## 7. URI Presentations

1. R. W. Schunk, The polar wind, *Invited Review*, Presented at "The First Huntsville Workshop on Magnetosphere-Ionosphere Plasma Models", October 13-16, 1986; Huntsville, Alabama.
2. A. R. Barakat, R. W. Schunk, T. E. Moore, and J. H. Waite, Ion escape fluxes in the terrestrial high latitude ionosphere, Presented at "The First Huntsville Workshop on Magnetosphere Ionosphere Plasma Models", October 13-16, 1986; Huntsville, Alabama.
3. R. W. Schunk, Ionosphere-thermosphere modelling: Current status, *Invited Review*, Presented at the International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System, December 2-5, 1986; Boulder, Colorado.
4. C. E. Rasmussen, R. W. Schunk, J. J. Sojka, V. B. Wickwar, O. de la Beaujardiere, J. C. Foster, and J. M. Holt, Comparison of simultaneous Chatanika and Millstone Hill temperature measurements with ionospheric model predictions, "International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System", December 2-5, 1986; Boulder, Colorado.
5. J. J. Sojka, and R. W. Schunk, Asymmetries in the plasma characteristics of the conjugate high-latitude ionospheres, "International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System", December 2-5, 1986; Boulder, Colorado.
6. C. E. Rasmussen, and R. W. Schunk, An *E* and *F* region density model for obtaining ionospheric conductivity, "International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System", December 2-5, 1986; Boulder, Colorado.
7. E. P. Szuszczewicz, E. Roelof, R. W. Schunk, B. Fejer, R. Wolf, R. Leitingner, M. Abdu, B M. Reddy, J. Joselyn, P. J. Wilkinson, and R. F. Woodman, SUNDIAL: A continuing program of global-scale modeling and measurement of ionospheric responses to solar, magnetospheric, and thermospheric controls, "International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System", December 2-5, 1986; Boulder, Colorado.
8. H. G. Demars, and R. W. Schunk, Comparison of solutions to bi-Maxwellian and Maxwellian transport equations for subsonic flows, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1136, 1986.
9. A. R. Barakat, and R. W. Schunk, Stability of the polar wind, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1136, 1986.
10. J. J. Sojka, and R. W. Schunk, Theoretical study of the high latitude ionosphere's response to multi-cell convection patterns, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1137, 1986.
11. R. J. Sica, C. E. Rasmussen, and R. W. Schunk, Can the high latitude ionosphere support large field-aligned ion drifts? AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1137, 1986.
12. R. W. Schunk, and J. J. Sojka, The lifetime and transport of severe ionospheric disturbances, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1137, 1986.

13. C. E. Rasmussen, and R. W. Schunk, Ionospheric convection driven by NBZ currents, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1162, 1986.
14. W. J. Raitt, J. V. Eccles, D. C. Thompson, P. M. Banks, R. I. Bush, and P. R. Williamson, Measurements of thermal electron energy distributions at the Space Shuttle orbiter near-wake edge, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1177, 1986.
15. D. C. Thompson and W. J. Raitt, The neutral gas environment about large vehicles in low earth orbit, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1177, 1986.
16. J. V. Eccles and W. J. Raitt, The electrodynamics of the plasmas within the outgas cloud of the Space Shuttle orbiter, AGU Fall Meeting, San Francisco, California; *EOS*, 67, 1177, 1986.
17. C. E. Rasmussen, and R. W. Schunk, Ionospheric convection driven by asymmetries in NBZ currents, National Radio Science Meeting, January 12-15, 1987; Boulder, Colorado.
18. R. W. Schunk, Implications of the SUNDIAL data on first-principles global-scale models, Presented at the "Third SUNDIAL Workshop", February 24-27, 1987; La Jolla, California.
19. R. W. Schunk, and J. J. Sojka, Ionospheric features induced by magnetospheric processes, *Invited Talk*, Presented at the International Symposium on Quantitative Modeling of Magnetosphere-Ionosphere Coupling Processes, March 9-13, 1987; Kyoto, Japan.
20. E. P. Szuszczewicz, E. Roelof, R. W. Schunk, B. Fejer, R. Wolf, M. Abdu, J. Joselyn, B. M. Reddy, P. Wilkinson, R. Woodman, and R. Leitingner, SUNDIAL: A global study of ionospheric processes and their roles in the transfer of energy and mass in the sun-earth system, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 68, 364, 1987.
21. R. W. Schunk, and E. P. Szuszczewicz, First-principle and empirical modeling of the global-scale ionosphere, *Invited Talk*, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 68, 364, 1987.
22. P. J. Wilkinson, R. W. Schunk, R. Hanbaba, and E. P. Szuszczewicz, Interhemispheric comparison of SUNDIAL *F*-region data with global-scale ionospheric models, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 68, 364, 1987.
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24. A. Khoyloo and W. J. Raitt, Modeling of contaminant plasmas in the Shuttle flowfield and  $N_2^+$  emissions, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1987.
25. R. W. Schunk, Characteristics of high voltage spheres in the ionosphere, Presented at the SPEAR meeting, W. J. Schafer, Inc., July 30, 1987; Arlington, Virginia.
26. R. W. Schunk, Polar wind theory, *Invited Review*, Presented at the 1987 Cambridge Workshop in Theoretical Geoplasma Physics on "Ionosphere-Magnetosphere-Solar Wind Coupling Processes", July 28-August 1, 1987; Cambridge, Massachusetts.



27. R. W. Schunk and E. P. Szuszczewicz, First-principal and empirical modelling of the global-scale ionosphere, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
28. R. J. Sica, C. E. Rasmussen, and R. W. Schunk, Can the high-latitude ionosphere support large field-aligned ion drifts?, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
29. C. E. Rasmussen and R. W. Schunk, Ionospheric convection driven by NBZ currents, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
30. A. R. Barakat and R. W. Schunk, Stability of the polar wind: Linear theory and simulation, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
31. C. E. Rasmussen and R. W. Schunk, An *E*- and *F*-region density model for obtaining ionospheric conductivity, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
32. C. E. Rasmussen, J. J. Sojka, R. W. Schunk, V. B. Wickwar, O. de la Beaujardiere, J. Foster, and J. Holt, Comparison of simultaneous Chatanika and Millstone Hill temperature measurements with ionospheric model predictions, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
33. J. J. Sojka, New results in modelling the global and high latitude ionospheric dynamics, Presented at the International Union of Geodesy and Geophysics, Vancouver, Canada; August 9-22, 1987.
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35. R. W. Schunk, Future thermospheric general circulation model (TGCM) needs, Presented at the Workshop on Atmospheric Density and Aerodynamic Drag Models for Air Force Operations, Boston, Massachusetts; October 20-22, 1987.
36. R. W. Schunk, Ionosphere-thermosphere interaction modelling; Current status, *Invited Paper*, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1382, 1987.
37. H. G. Demars, and R. W. Schunk, Temperature anisotropies in the ionosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1382, 1987.
38. J. J. Sojka, and R. W. Schunk, A model study of how electric field structures affect the polar cap *F*-region, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1385, 1987.
39. A. R. Barakat, and R. W. Schunk, Effect of cusp  $H^+$  and  $O^+$  beams on the stability of the polar wind, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1386, 1987.
40. T.-Z. Ma, and R. W. Schunk, A fluid model of high voltage spheres in the ionosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1402, 1987.

41. W.-H. Yang, and R. W. Schunk, A model of solar wind streams, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1410, 1987.
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43. J. Liu, C. E. Rasmussen, R. J. Sica, A. D. Richmond, and R. W. Schunk, Motion of ionospheric flux tubes during a period of substorm activity, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1430, 1987.
44. J. V. Eccles, W. J. Raitt, and P. M. Banks, The effect of plasma electrodynamics on the chemistry within the outgas cloud of the Space Shuttle Orbiter, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1987.
45. D. C. Thompson, and W. J. Raitt, The interaction of neutral contaminant gases introduced by orbiting spacecraft with the ambient terrestrial atmosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 68, 1987.
46. R. W. Schunk, and J. J. Sojka, Modelling ionospheric density structures, *Invited Talk*, Presented at the National Radio Science Meeting, January 5-8, 1988; Boulder, Colorado.
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48. C. E. Rasmussen, and R. W. Schunk, A three-dimensional time-dependent model of the plasmasphere, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 428, 1988.
49. R. W. Schunk, and J. J. Sojka, A three-dimensional time-dependent model of the polar wind, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 429, 1988.
50. J. J. Sojka, and R. W. Schunk, Modelling ionospheric density structures and dynamic auroral features, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 431, 1988.
51. T.-Z. Ma, and R. W. Schunk, A two-dimensional model of plasma expansion in the ionosphere, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 431, 1988.
52. N. C. Maynard, R. W. Schunk, J. J. Sojka, J. P. Heppner, and L. A. Brace, A test of the applicability of magnetospheric convection models for northward IMF conditions, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 415, 1988.
53. R. J. Sica, R. W. Schunk, and C. E. Rasmussen, Maximum field-aligned plasma velocities in the *F*-region, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 443, 1988.
54. W. J. Raitt, H. Long, and J. V. Eccles, Measurements of non-Maxwellian velocity distributions using a spherical retarding potential analyzer (SRPA), AGU Spring Meeting, Baltimore, Maryland; *EOS*, 69, 1988.
55. R. W. Schunk, and J. J. Sojka, Modelling ionospheric density structures, AGARD Symposium on 'Ionospheric Structure and Variability on a Global Scale and Interaction with Atmosphere, Magnetosphere', 16-20 May, 1988; Munich, West Germany.

56. R. W. Schunk, Polar wind tutorial, *Invited Lecture*, Presented at the 1988 Cambridge Workshop in Theoretical Geoplasma Physics on 'Polar Cap Dynamics and High Latitude Ionospheric Turbulence', 13-17 June, 1988; Cambridge, Massachusetts.
57. R. E. Daniell, L. D. Brown, D. N. Anderson, J. J. Sojka and R. W. Schunk, A real-time high latitude ionospheric specification model, Presented at the 1988 Cambridge Workshop in Theoretical Geoplasma Physics on 'Polar Cap Dynamics and High Latitude Ionospheric Turbulence', 13-17 June, 1988; Cambridge, Massachusetts.
58. R. W. Schunk, Magnetosphere-ionosphere-thermosphere coupling processes, *Invited Talk*, Presented at the SCOSTEP special session on Solar-Terrestrial Energy Program (STEP): Major Scientific Problems, 18-29 July, 1988; Helsinki, Finland.
59. R. W. Schunk, Response of the ionosphere-thermosphere system to magnetospheric forcing, *Invited Talk*, COSPAR 27<sup>th</sup> Plenary Meeting, 18-29 July, 1988; Helsinki, Finland.
60. A. R. Barakat and R. W. Schunk, Outflow of low energy ions in the terrestrial high-latitude ionosphere, *Invited Talk*, COSPAR 27<sup>th</sup> Plenary Meeting, 18-29 July, 1988; Helsinki, Finland.
61. A. R. Barakat and R. W. Schunk, Stability of the polar wind in the presence of cusp  $H^+$  and  $O^+$  ions, COSPAR 27<sup>th</sup> Plenary Meeting, 18-29 July, 1988; Helsinki, Finland.
62. H. G. Demars and R. W. Schunk, Solutions to bi-Maxwellian transport equations for the solar wind, American Physical Society Topical Conference of Plasma Astrophysics, 19-23 September, 1988; Santa Fe, New Mexico.
63. R. W. Schunk and W.-H. Yang, Modeling high-speed solar wind streams, American Physical Society Topical Conference of Plasma Astrophysics, 19-23 September, 1988; Santa Fe, New Mexico.
64. W.-H. Yang, Force-free magnetic field model of accretion disk, American Physical Society Topical Conference of Plasma Astrophysics, 19-23 September, 1988; Santa Fe, New Mexico.
65. R. W. Schunk and J. J. Sojka, Global polar wind variations during changing magnetospheric conditions, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1340, 1988.
66. H. Thiemann and R. W. Schunk, Sheath formation around biased interconnectors and current collection in a LEO-plasma as seen by PIC simulations, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1378, 1988.
67. J. J. Sojka and R. W. Schunk, Theoretical study of the seasonal behavior of the global ionosphere at solar maximum, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1349, 1988.
68. H. G. Demars and R. W. Schunk, Solutions to bi-Maxwellian transport equations for the solar wind, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1364, 1988.
69. W. -H. Yang and R. W. Schunk, Modelling high-speed solar wind streams, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1358, 1988.

70. R. J. Sica, R. W. Schunk, and P. Wilkinson, An empirical study of the undisturbed mid-latitude ionosphere using simultaneous, multiple site ionosonde measurements, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1350, 1988.
71. C. E. Rasmussen and R. W. Schunk, Comparison of plasmaspheric measurements with a three-dimensional time-dependent model of the plasmasphere, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1347, 1988.
72. N. B. Myers, W. J. Raitt, P. M. Banks, P. R. Williamson, B. E. Gilchrist, and S. Sasaki, The current-voltage relationship of an electron beam-emitting sounding rocket payload in the ionosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1368, 1988.
73. J. Roberts and W. J. Raitt, Observations of enhanced current collection by high voltage conductors at LEO altitudes arising from platform gas release, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1368, 1988.
74. D. C. Thompson and W. J. Raitt, The interaction of contaminant neutral gases introduced by orbiting spacecraft with the atmosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1371, 1988.
75. H. Long, W. J. Raitt, D. C. Thompson, and J. V. Eccles, The distribution function of contaminant ions produced by an outgassing orbital platform in the Earth's ionosphere, AGU Fall Meeting, San Francisco, California; *EOS*, 69, 1371, 1988.
76. R. W. Schunk, Streamlining theoretical ionospheric models for practical applications, *Invited Talk*, Presented at the National Radio Science Meeting, January 4-6, 1989; Boulder, Colorado.
77. R. E. Daniell, L. D. Brown, D. N. Anderson, J. J. Sojka, and R. W. Schunk, A parameterized analytic model of the high latitude ionosphere, National Radio Science Meeting, January 4-6, 1989; Boulder, Colorado.
78. W. J. Raitt, Interaction of the outgas cloud from a space platform with the ambient environment at LEO altitude, *Invited*, Presented at Space Vehicle and Environment Interaction Workshop, Johns Hopkins University/Applied Physics Laboratory, February 21-22, 1989; Laurel, Maryland.
79. J. J. Sojka and R. W. Schunk, Ionospheric specification model, Presented at the Third Quarterly Meeting of the Air Weather Services (AWS) Ionospheric Specification Modelling, April 18-19, 1989; Houston, Texas.
80. R. J. Sica, R. W. Schunk, and P. J. Wilkinson, A study of the undisturbed mid-latitude ionosphere using simultaneous, multiple site ionosonde measurements, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 70, 410, 1989.
81. R. W. Schunk, Current status of numerical ionospheric modelling, *Invited Talk*, AGU Spring Meeting, Baltimore, Maryland; *EOS*, 70, 406, 1989.
82. V. B. Wickwar and R. W. Schunk, The high-latitude *F* region: Observation and theory, *Invited Talk*, Presented at the Fourth EISCAT Scientific Workshop, 5-9 June, 1989; Sigtuna, Sweden.

83. D. Rees, V. B. Wickwar, R. Sica, and R. W. Schunk, Mid-latitude thermospheric dynamics under quiet and disturbed conditions, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 365, 1989.
84. E. Szuszczewicz, R. Wolf, B. G. Fejer, E. Roelof, and R. W. Schunk, SUNDIAL: A coordinated multiparameter measurements and modelling program on the prediction and control of the global scale ionosphere: A review of progress, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 350, 1989.
85. V. B. Wickwar, K. L. Miller, R. W. Schunk, D. Alcayde, G. S. Ivanov-Kholodny, R. W. Smith, and P. J. Wilkinson, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 350, 1989.
86. T.-Z. Ma and R. W. Schunk, A 3-D model for plasma clouds in the ionosphere, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 393, 1989.
87. H. Thiemann and R. W. Schunk, Secondary emission as a trigger mechanism for anomalous features in solar array-plasma interactions, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 393, 1989.
88. R. W. Schunk and E. P. Szuszczewicz, Plasma expansion phenomena: Comparison of characteristics predicted by small-scale and macroscopic formulations, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 393, 1989.
89. R. W. Schunk and J. J. Sojka, Global polar wind variations driven by magnetospheric processes, IAGA Scientific Assembly, 24 July-4 August, Exeter, England; *IAGA Bulletin*, 53, 309, 1989.

## 8. URI Travel Summary

1. Intl Workshop- Large Scale Processes in the Ionosphere/Thermosphere  
Boulder, Colorado  
12/1-12/5/86  
Schunk, Rasmussen, and Sojka presented papers.
2. Fall American Geophysical Union Meeting  
San Francisco, California  
12/7-12/12/86  
Schunk, Barakat, Rasmussen, Demars, and Bowline presented papers.
3. URSI International Meeting  
Boulder, Colorado  
1/11-1/13/87  
Schunk and Rasmussen presented papers.
4. SUNDIAL Meeting  
San Diego, California  
2/23-2/27/87  
Schunk- to compare ionospheric model predictions with measurements.
5. AFGL Meeting  
Boston, Massachusetts  
3/29-4/1/87  
Initiate cooperative efforts between USU & AFGL scientists.  
Presentations made:  
Schunk - Overview of the USU Center of Excellence in Theory and Analysis of the Geoplasma Environment;  
Sojka - Status of Large Scale Ionospheric-Thermospheric Modelling at USU;  
Barakat - Stability of the Polar Wind;  
Rasmussen - Modeling of Plasma Convection in the High-Latitude Ionosphere;  
Raitt - Experimental Space Plasma Physics.
6. Meeting with Dave Evans  
Boulder, Colorado  
4/27-4/29/87  
Sojka and Hand attended.
7. Spring American Geophysical Union Meeting  
Baltimore, Maryland  
5/17-5/20/87  
Schunk presented papers.
8. AFGL Meeting  
Boston, Massachusetts  
6/17-6/20/87  
Sojka meeting to discuss collaborative projects.

9. CEDAR/GISMOS Workshop  
Boulder, Colorado  
6/25-6/29/87  
Schunk, Sojka, and Sica meetings to compare ionospheric model predictions with measurements.
10. AFOSR Supported Research  
Colorado Springs, Colorado  
6/29-7/2/87  
Hand attended satellite drag meeting.
11. AFGL Meeting  
Boston, Massachusetts  
7/12-7/14/87  
Rasmussen attended meetings to discuss collaborative projects.
12. AFGL Meeting  
Boston Massachusetts  
7/26-8/2/87  
Schunk, Sica, and Yang attended meetings to discuss collaborative projects with H. Carlson, E. Weber, Bauchau, J. Whalen, C. Sherman, and S. Basu;  
Schunk and Yang attended MIT Cambridge Workshop and presented papers;  
Schunk also attended the Soviet Ionospheric Modification Workshop, Spacecraft Contamination Meeting, and SUNDIAL Meeting in Washington, D. C.
13. IAGA International Meeting  
Vancouver, Canada  
8/16-8/21/87  
Schunk, Sojka, Rasmussen, and Barakat presented papers.
14. TEX Macro Workshop  
Chicago, Illinois  
9/13-9/18/87  
Selzer attended workshop on macro writing for final typeset copy.
15. AFOSR Supported Research  
Colorado Springs, Colorado  
10/18-10/10/21/87  
Hand attended meetings on satellite drag.
16. AFOSR Supported Research  
Boston, Massachusetts  
10/19-10/22/87  
Schunk attended workshop on atmospheric density and aerodynamic drag models for Air Force operations.

17. AGU Fall Meeting  
San Francisco, California  
12/7-12/11/87  
Schunk, Sojka, Rasmussen, Sica, Yang, Ma, Demars, and Barakat presented papers.
18. National Radio Science Meeting  
Boulder, Colorado  
1/5-1/8/88  
Schunk presented a paper.
19. NATO/AGARD Symposium  
Munich, Germany  
5/16-5/20/88  
Schunk presented a paper and was co-chairman of the meeting.
20. 1988 Cambridge Workshop  
Boston, Massachusetts  
6/13-6/17/88  
Schunk attended and two papers presented.
21. COSPAR International Meeting  
Helsinki, Finland  
7/18-7/29/88  
Schunk presented four papers and chaired two sessions.
22. AFGL Meeting  
Boston, Massachusetts  
9/6-9/7/88  
Schunk and Sojka visit to discuss collaborative efforts.
23. American Physical Society Meeting  
Santa Fe, New Mexico  
9/19-9/23/88  
Demars and Yang presented three papers.
24. AGU Fall Meeting  
San Francisco, California  
12/5-12/9/88  
Seven papers were presented;  
Schunk met with H. Carlson to discuss future AWS needs for ionospheric & thermospheric real-time modelling;  
Schunk & Sojka met with N. Maynard to discuss the first draft of a joint paper;  
Schunk & Sojka met with D. Anderson & H. Kroehl to discuss USU computer simulations that were done for the AWS ionospheric specification model.



25. National Radio Science Meeting  
Boulder, Colorado  
1/4-1/6/89  
Schunk attended and two papers were presented.
26. Meeting at NOAA  
Boulder, Colorado  
1/6/89  
Schunk met with several scientists (D. Anderson, R. Daniell, H. Kroehl, R. Roble, A. Richmond) to discuss AWS modelling plans.
27. AWS Meeting  
Houston, Texas  
4/18-4/19/89  
Schunk & Sojka attended.
28. AGU Spring Meeting  
Baltimore, Maryland  
May, 1989  
Schunk attend and presented two papers.
29. IAGA Scientific Assembly  
Exeter, England  
7/24-8/4/89  
Schunk & Ma attended and seven papers were presented.

## 9. URI Personnel

### Ph.D. Scientists

R. W. Schunk — P.I.  
A. R. Barakat  
H. G. Demars  
B. G. Fejer  
T.-Z. Ma  
W. J. Raitt  
C. E. Rasmussen  
R. J. Sica  
J. J. Sojka  
H. Thiemann  
W.-Y. Yang

### Graduate Students

A. Khoyloo  
K. Kikuchi  
M. Dwyer — AWS  
K. Hand — AWS  
G. Huffines — AWS  
G. Wells — AWS

### Undergraduate Students

M. Bowline  
M. Hossein  
E. Kluzek  
J. Liu  
K. O'Rourke  
P. Stanley

### Administrative Support

T. Dull  
D. Loges  
J. Selzer

## COMPLETED PROJECT SUMMARY

TITLE: USU Center of Excellence in Theory and Analysis of the Geo-Plasma Environment

PRINCIPAL INVESTIGATOR: Professor R. W. Schunk  
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#### ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

The primary objective of this three-year research effort was to elucidate the coupling processes, time delays, and feedback mechanisms between the different regions of the magnetosphere-ionosphere-atmosphere system. Another important goal was to study the production, transport and decay of large-scale ionospheric density structures. Additional research tasks include the following: (1) Investigate the effect of multi-cell convection patterns, plasma blob formation, and sun-aligned arcs on the high-latitude ionosphere; (2) Investigate the coupling of the high, middle, and low latitude regions of the ionosphere; (3) Study the effect of electrodynamic drifts, propagating density fronts, and shock formation on the dynamics of the inner magnetosphere; (4) Initiate the development of a thermospheric general circulation model; (5) Couple global models of ionospheric conductivity, electric fields, and currents in order to study seasonal effects, hemispheric asymmetries, and the effects of discrete arcs on ionospheric-magnetospheric dynamics; (6) Investigate ionosphere-magnetosphere coupling in the high-latitude region; (7) Study various spacecraft-environment interaction problems, including outgassing from the Space Shuttle, contaminant plasma cloud dynamics, the interaction of high voltage components with the ionosphere, and solar array-plasma interactions at LEO altitudes; and (8) Assist in the development of the High-Latitude Ionospheric Specification Model, which will be used by Air Weather Services.

Some of our important accomplishments are described in the following statements:

1. From our model studies concerning the origins, lifetimes, and transport characteristics of

large-scale ionospheric density structures, we found that the lifetime of an F-region density structure depends on several factors, including the initial location where it was formed, the size of the structure, the season, the level of solar activity, and the direction of the interplanetary magnetic field (IMF). For example, in summer the density perturbation associated with the structure can disappear in a few hours or last as long as 9 hours, while in winter a density structure can persist for as long as 24 hours.

2. We found that the transport characteristics of density structures are governed by the plasma convection pattern, which is a strong function of the IMF. Depending on the IMF, a given density structure can remain intact as it convects, become elongated, or break up into multiple segments that convect in different directions.
3. Fifty-four numerical simulations of the high-latitude ionosphere were conducted in support of the development of the High Latitude Ionospheric Specification Model for Air Weather Services. The simulations covered a range of solar cycle, seasonal, magnetic activity, and IMF conditions.
4. Numerous model/data comparisons were conducted in order both to validate our ionospheric model and to determine the input parameters needed for real-time ionospheric modelling. We found that the downward electron flux from the magnetosphere is an important input parameter for the F-region models, and yet, it is virtually unknown at high latitudes.
5. We found that the different plasma convection patterns display distinct ionospheric signatures, particularly for northward IMF when 3-cell, 4-cell, or severely distorted 2-cell patterns can exist. In one study involving data from the Dynamics Explorer satellite, we found a definite preference for the severely distorted 2-cell convection pattern.
6. From our studies involving plasma coupling between the ionosphere and magnetosphere at high latitudes, we found that cusp-generated ion beams passing through the polar wind can be unstable depending on the ion beam/background density ratio and the electron/ion temperature ratio. Unstable plasma conditions have a dramatic effect on the momentum and energy coupling between the ionosphere and magnetosphere.
7. The preliminary version of a thermospheric general circulation model has been developed. The model was based on a numerical solution of the coupled continuity, momentum, and energy equations for the neutral gas including interactions with ionospheric electrons and ions. The model is a time-dependent, 3-dimensional, high-resolution, multi-species model and it was designed so that the global grid system is arbitrary.
8. We developed a time-dependent, 3-dimensional, nonlinear, multi-species model of the outer plasmasphere. In the first application of the model, we found that plasmaspheric refilling after geomagnetic storms can only be understood if the convection history of the flux tube is known.
9. From our simulations of the interaction of a high-voltage sphere with the plasma environment at LEO altitudes, we found that in response to an applied positive voltage an electron density torus forms around the sphere in the equatorial plane at early times. Later, the outer edge of the torus becomes elongated along the geomagnetic field and the bulk of the region perturbed by the sphere is contained within a cylindrical volume (governed by the Parker-Murphy collection radius).
10. From our studies concerning outgassing from the Space Shuttle at LEO altitudes, we found that in the vicinity of the Space Shuttle the contaminant neutral density is two orders of magnitude greater than the ambient neutral density and the contaminant plasma density is one order of magnitude greater than typical ionospheric densities. The perturbations created



by the Shuttle can take many hours to dissipate, depending on the outgassing and ambient conditions.

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